Experimental Investigation of 3D Scanheads for Laser Micro Processing

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Experimental Investigation of 3D Scanheads for Laser Micro Processing

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Abstract

The broader use of laser micro processing technology increases the demand for executing complex machining and joining operations on free-from (3D) workpieces. To satisfy these growing requirements it is necessary to utilise 3D scanheads that integrate beam deflectors (X and Y optical axes) and Z modules with high dynamics. The research presented in this communication proposes an experimental technique to quantify the dynamic capabilities of Z modules, also called Dynamic Focusing Modules (DFM), of such 3D scanheads that are essential for efficient, accurate and repeatable laser micro processing of free form surfaces. The proposed experimental technique is validated on state-of-art laser micro-machining platform and the results show that the DFM dynamic capabilities are substantially inferior than those of X and Y beam deflectors, in particular the maximum speed of the Z module is less than 10% of the maximum speeds achievable with X and Y optical axes of the scanhead. Thus, the DFM dynamics deficiencies can become a major obstacle for the broader use of high frequency laser sources that necessitate high dynamics 3D scanheads for executing cost effectively free-form surface processing operations.

Keywords: laser micro processing; 3D scanheads; dynamic focusing module; dynamic capabilities

1. Introduction

Laser micromachining (LMM) has attracted a significant industrial interest due to its intrinsic machining advantages such as non-contact processing of free-from (3D) workpieces in a wide range of materials [1]. Thus, the demands for complex laser machining and also joining operations, which require the synchronized utilization of optical axes (X, Y, and Z) with high dynamics capabilities, are exponentially growing [2]. A literature review reveals that the dynamics capabilities of X and Y beam deflectors of 3D scanheads have been thoughtfully studied, but those of their Z modules, also called Dynamic Focusing Modules (DFM), have been overlooked. To the authors' knowledge, investigations of DFM dynamics capabilities have not been reported, with the exception of one laser scanhead manufacturer that has provided some information about product dependent dynamics specifications of a Z module [3].

DFMs are built in two different configurations, which are schematically presented in Figure 1. Figure 1a shows a beam expander DFM configuration, which consists of a diverging optic that can be translated coaxially along the optical beam path via a linear motor, and a stationary focusing optic. In contrast, Figure 1b shows a beam condenser DFM configuration, which includes a converging optic and a stationary focusing optic. Choice of a suitable DFM configuration for a particular laser system is dependent on the laser beam characteristics of the used laser source such as beam waist diameter and collimation, because DFM optics are selected to give minimum laser beam aberrations. Examples of laser beam aberrations caused by a lens that have to be taken into account when selecting a DFM configuration include spherical aberrations, chromatic aberrations and aperture diffraction [4]. Even though, DFMs are supplied in two different configurations, their working principles are the same. In particular, movements of the diverging or converging optics during a laser processing operation changes the relative distance between the moveable and the stationary optics, which causes changes in laser system's focal length and thus the laser beam spot can be focussed at different planes along its propagation axis (z axis) [3].

The aim of this research is to design an experimental technique that can evaluate the dynamic capabilities of DFMs and thus to judge about their negative effects in laser micro-processing of complex free-form (3D) surfaces. The next section introduces the proposed experimental technique and then experimental results are discussed and conclusions are drawn.

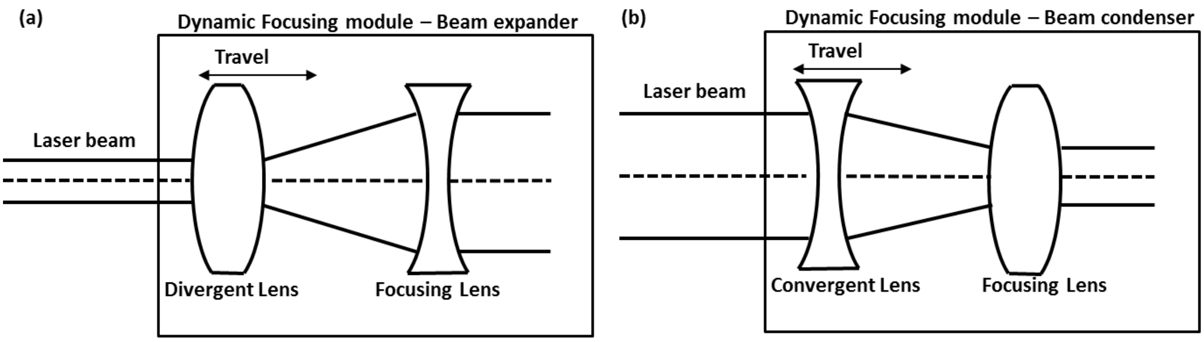

Figure 1. DFM configurations: (a) beam expander DFM and (b) beam condenser DFM.

2. Experimental

2.1 Equipment

Experiments were performed on a state-of-art laser micromachining (LMM) platform that incorporates a 3D scanhead for focusing a beam with high dynamics within 35 mm (X) x 35 mm (Y) x 7.7 mm (Z) processing envelop defined by a 100 mm telecentric lens. The LMM platform utilizes a state-of-art representative beam condenser DFM configuration that has a beam condensation factor of 0.75. Furthermore, the LMM platform is equipped with three linear and two rotary stages that can be used for precise repositioning of 3D scanhead processing envelop within the laser system's working envelop , in particular their positioning resolutions are 0.25 µm and 45 µrad, respectively [5,6]. The accuracy, repeatability and reproducibility (ARR) achievable with the X and Y optical beam deflectors of the 3D scanhead has been studied and they are better than +/- 5 µm across the full range of achievable scanning speeds (up to 4m/s for the used focusing lens) [7]. The LMM platform integrates a SPI redENERGY G4 S-type 50 W nanosecond (ns) fibre laser that has a central wavelength of 1064 nm and supports repetitions rates up to 1 MHz and pulse durations in the range from 15 ns to 220 ns. The beam quality factor (M^2) of this laser source is better than 1.2.

The spatial profile of the laser beam is characterized by utilizing a Dataray Beam R2 scanning slit beam profiler that can be used to measure tightly focused laser beams [8].

The experimental results were analysed on a Focus Variation (FV) optical microscope, namely Alicona G5 [9], while the analytical procedure was repeated five times for each laser machining trial.

The measurements were performed using a x20 magnification lens that has measurement uncertainty of 0.01 µm [9] and the Alicona Profile tool was employed to process the acquired data.

2.2 Methodology

Figure 2 presents the test sample used to evaluate the DFM dynamics capabilities. In particular, the experiments involved the machining of 30 mm long tracks with dimples produced on two SS 316 samples with different scanning speeds, V_1, V_2 …V_n, one sample is normal and the other is tilted at 15^o in regards to the incident beam. Table 1 provides the laser parameters utilized to machine the laser tracks. Twelve laser tracks were produced at different scanning speeds, but it should be noted that each laser track is produced with constant scanning speed. The title angle of 15^o was selected in order to fit the machined area on the sample within the focusing envelop of the used 3D scanner and focusing lens, in particular within the enveloped defined by the DFM Z range (7.7 mm) and the focusing lens's field of view (35 x 35 mm) as mentioned in Section 2. The sample was tilted by employing the rotary stage, which rotates the sample about the x axis of the workpiece and thus the tilt is along its y axis as shown in Figure 2. Thus, the laser tracks on the tilted sample were produced along its y axis. In this way the movements along the tilted axis have components both along the y and z axes and thus DFM has to be utilized in combination with the X-Y optical beam deflector system. The steps between the dimples along the laser tracks are 100 µm, while the step-over distance between the laser tracks was set to 150 µm. Furthermore, the dimple diameter was determined by the laser beam spot diameter, because there was no overlapping of pulses in each laser scan. The tracks were produced by 15 repeated scans and thus each dimple was created by a sequence of 15 laser pulses. In this way the target dimple depth of 12 µm was achieved. Also, it should be noted that the laser tracks both on the tilted and the normal samples were produced with an offset from the focal plane that is equal to the Rayleigh length (z_R) as shown in Figure 3, where z_R can be calculated using Equation 1. Furthermore, to account for any laser beam focus aberrations caused by the optics, the offset from the focal plane was also experimentally determined by measuring the distance at which the beam spot diameter is equal to sqrt(2)*w_0 (Rayleigh length criterion) by utilizing the beam analyser.

$$z_R = \frac{\pi \times w_0^2}{\lambda \times M^2} \qquad \text{Equation 1}$$

where: w_0 is the focused beam spot radius, λ - the wavelength of the laser beam and M^2 - the laser beam quality factor.

The DFM dynamic capabilities were assessed by analysing the depth profiles' differences of the dimples produced on the tilted and the normal plates to the incident beam.

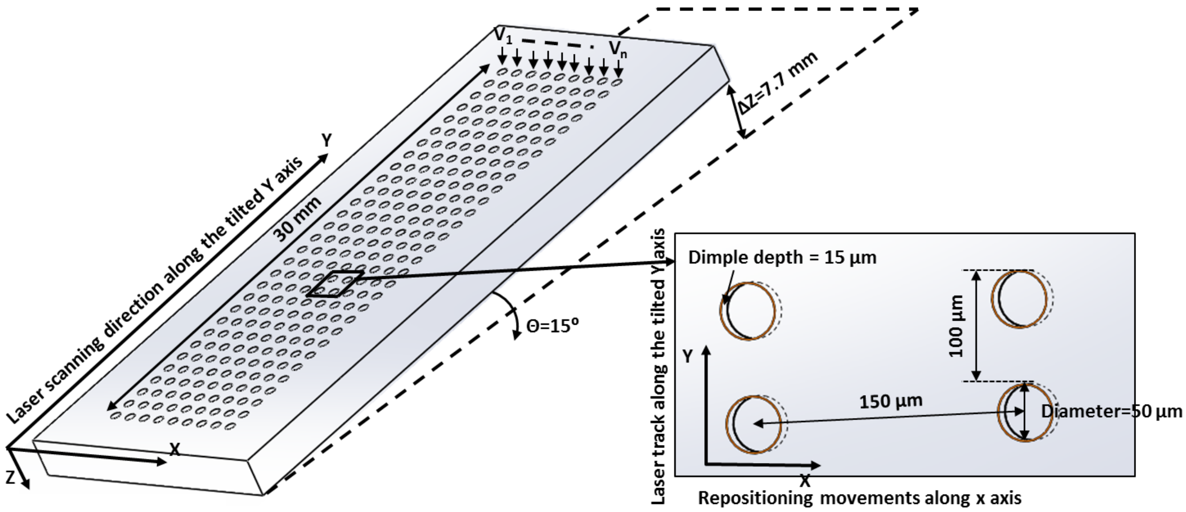

Figure 2. The test sample used to evaluate the DFM dynamic capabilities.

Note: The laser tracks are produced along the tilted Y axis of the workpiece, while laser beam repositioning movements before the machining of each laser tracks (non-machining movements) are executed along the x-axis of the workpiece.

Table 1. Laser parameters for the experimental tests

Laser track	1	2	3	4	5	6	7	8	9	10	11	12
Average Power [W]	40											
Pulse duration [ns]	220											
Beam diameter at focus [µm]	63											
Frequency [kHz]	1	5	10	12	13	14	15	16	17	18	19	20
Scanning Speed [m/s]	0.1	0.5	1.0	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0

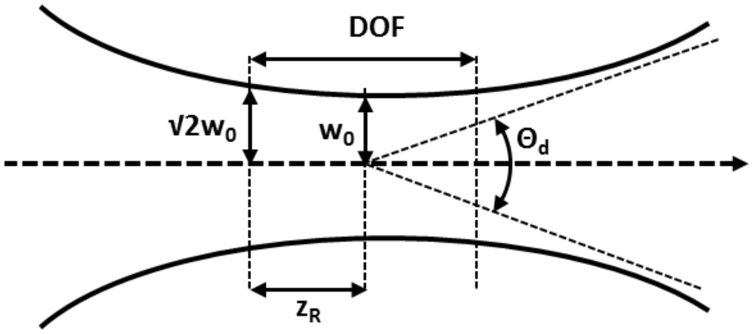

Figure 3. Rayleigh length criterion

3. Results and Discussions

Figure 4 shows that the laser beam spot diameter at the focal plane and at an offset distance equal to the Rayleigh length above the focal plane are 63 μm and 89 μm, respectively. The offset distance calculated using Equation 1 was 2.45 mm and it resulted in a laser beam Depth of Focus (DOF) of 5.9 mm, twice the Rayleigh range (see Figure 3). Since, DOF is comparable to the DFM Z range, it greatly impairs the deterministic evaluation of the DFM dynamic capability. This is because DOF compensates the "lagging" of the laser beam movement along the z-axis that is due to the DFM insufficient dynamics capability. Thus, the depth profiles of the produced dimples will be similar, because the changes of energy density (fluence) can be considered negligible within the beam DOF. Therefore, it is necessary to reduce substantially and even to eliminate the DOF compensation effects on dimples' depth profiles. This can be achieved by producing the laser tracks at an offset distance equal to Rayleigh length, 2.45 mm in our case, and thus any further displacements of the laser beam from the focal plane due to insufficient DFM dynamic capabilities to lead to a significant difference of energy densities and as a consequence of this to dimples' depth profiles.

Figure 5a shows a 3D view of all produced laser tracks on the sample normal to the incident beam (no movements with DFM along the Z axis), while Figure 5b provides a magnified top view of the area at the end of the tracks. It can be judged visually in Figure 5b that the dimples have very similar profiles regardless of the scanning speeds. In addition, Figure 5c provides the depths of the dimples produced at all processing speeds and they are very similar, approximately 12 µm. Also, it can be seen in Figure 5b that there are small errors/differences in the laser tracks produced at different scanning speeds. They can be explained with the fact that any small variations of the scanning speeds caused by torsional resonance, heat dissipation, drift, nonlinearities, noise and calibration routines [7], are amplified since the there is no pulse overlapping and each dimple is the results of 15 pulses. Thus, even small beam positional errors are revealed and accumulated along the 30 mm long tracks even though they do not affect the overall accuracy of the 3D scanhead in executing the machining vectors. In particular, if there is a pulse overlap any small variations of scanning speeds in producing the dimples will not be noticeable at the end of the tracks.

Figure 6 depicts the carried out measurements of the dimples produced on the tilted sample. It can be clearly see in Figure 6b that the topography of the dimples changes with the increase of the scanning speed. For example, the dimples are barely visible at a speed of 2 m/s (the rightmost laser track in Figure 6b). Furthermore, Figure 6c provides the depth profiles of the dimples produced at all processing speeds. It can be clearly seen that at processing speeds above 1500 mm/s, the dimples do not have the expected depth of 12 µm. This should be attributed to the DFM inability to follow closely the surface that is not normal to the incident beam along the z axis with the required dynamics. A comparison of the results in Figure 5 and Figure 6 reveals that the DFM dynamics is sufficient only up to a scanning speed of 1500 mm/s. In particular, DFM can execute beam movements along the Z axis without lags, synchronously with X and Y movements, only if the required speed does not exceed 388 mm/s ($\sin \Theta * V$) and thus it is less than 10 % of the maximum V achievable with the X and Y beam deflectors of the investigated system in this research, in particular 4 m/s.

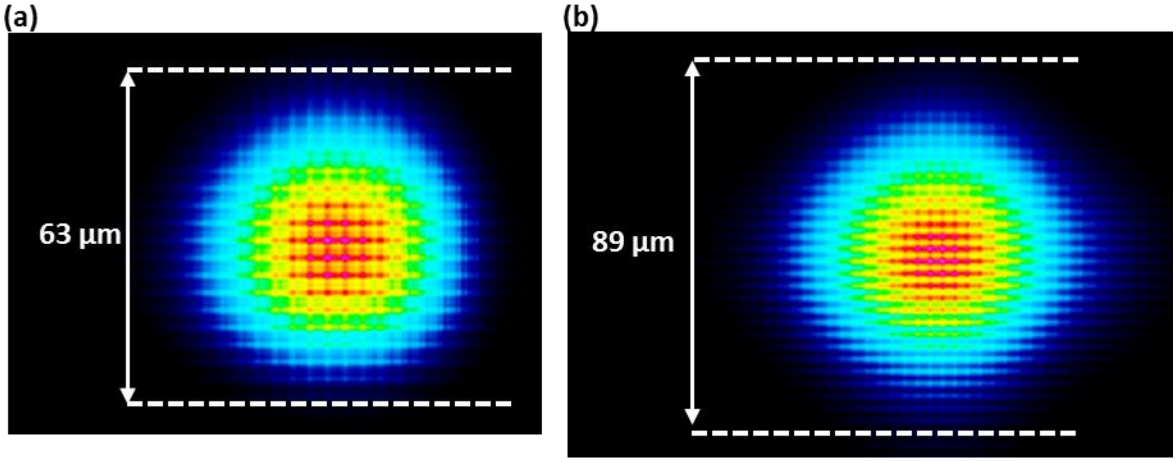

Figure 4. Laser beam energy profiles (a) at the focal plane (z=0) and at an offset distance of 2.45 mm above the focal plane (z=+2.45 mm).

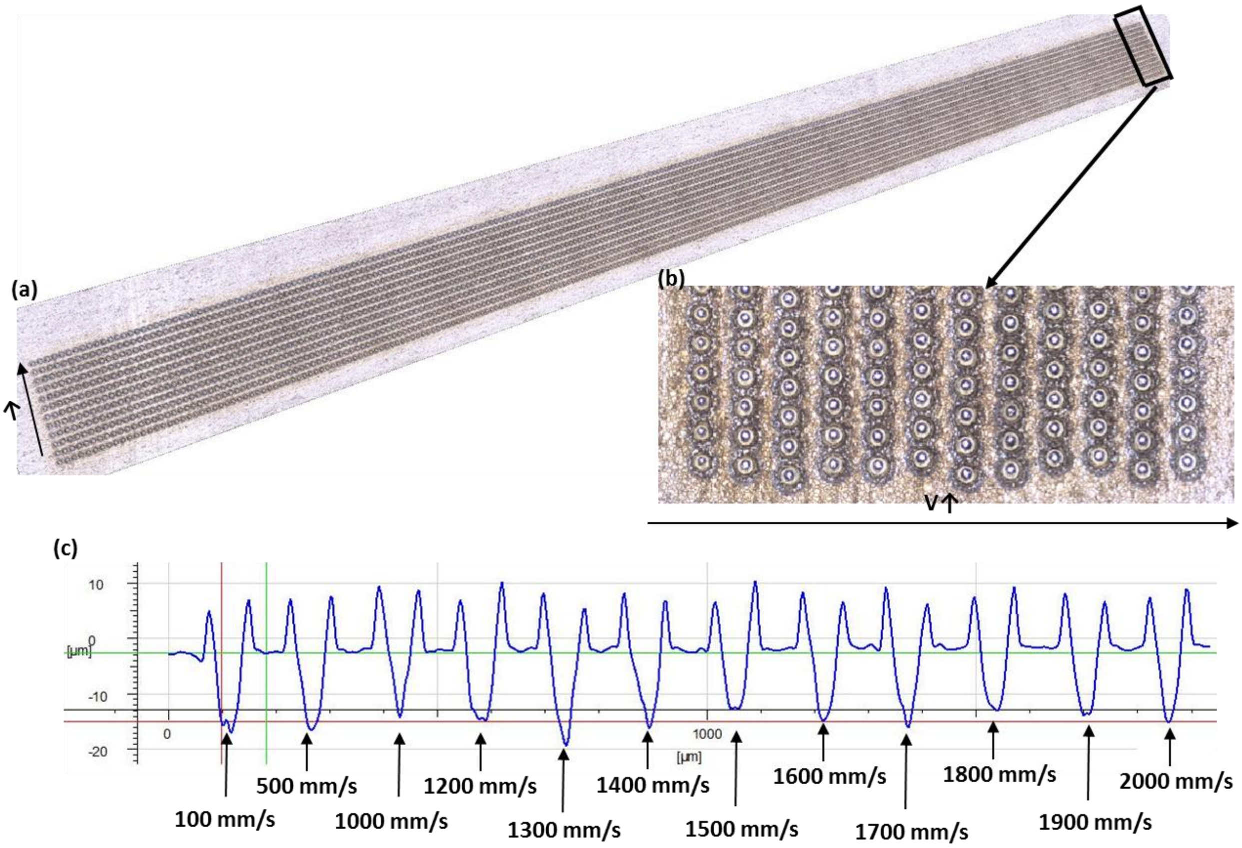

Figure 5. Laser tracks produced at different scanning speeds on the SS 316 sample when it is normal to the incident beam: (a) 3D view of the produced laser tracks; (b) magnified view of the area at the

end of the laser tracks (the scanning speed is increasing from left to right); (c) depth profile of dimples at the end of the laser tracks.

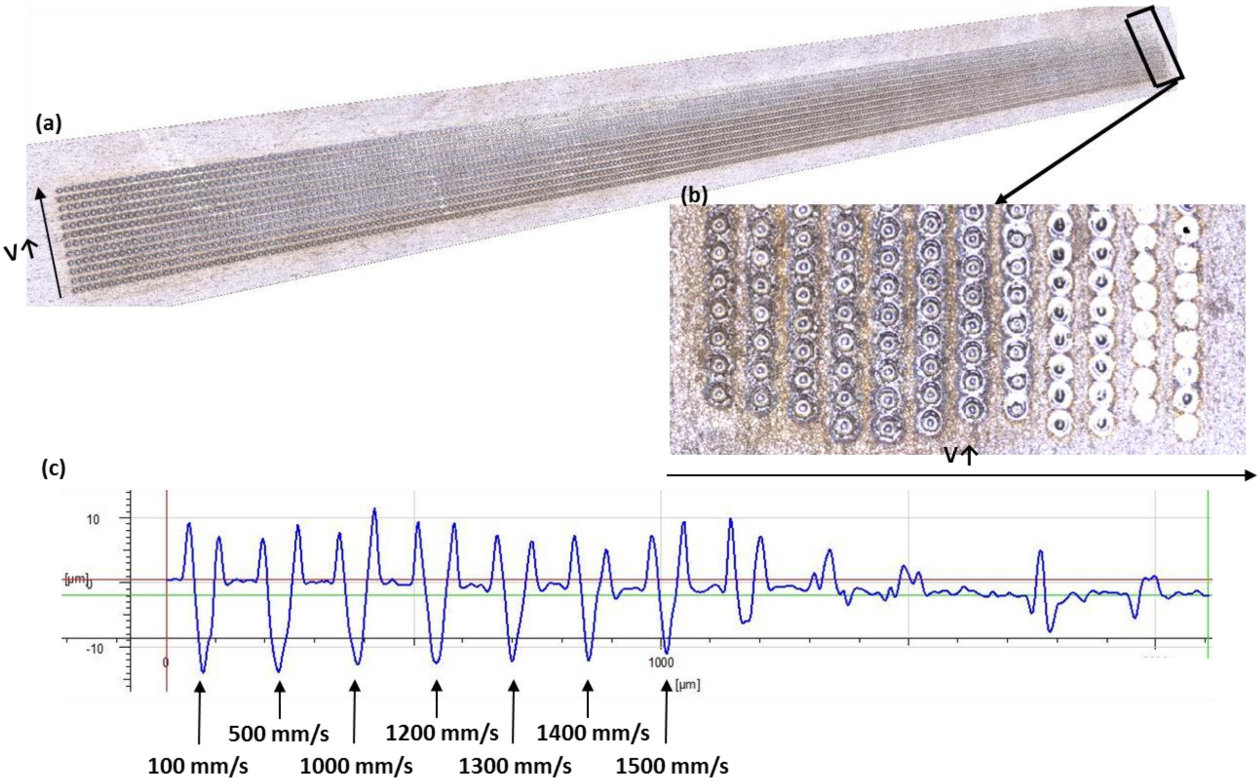

Figure 6. Laser Tracks produced at different scanning speeds on the SS 316 sample at Θ=15^o to the incident beam: (a) 3D view of the produced laser tracks; (b) magnified view of the area at the end of the laser tracks (the scanning speed is increasing from left to right); (c) depth profile of dimples at the end of the laser tracks.

4. Conclusions

The presented research proposes an experimental technique to assess the DFM's dynamic capabilities. The results show that at high speeds of the X and Y beam deflectors the depth of focus of the used laser micro processing setups may not be sufficient to compensate the lag in executing the necessary Z movements when processing free form surfaces. In such cases it will be necessary to reduce the X and Y beam deflectors' speeds of the 3D scanheads and thus to operate below the max speeds achievable by any given DFM when performing laser structuring or texturing operation on free form surfaces in order to achieve the required accuracy and repeatability. This DFM deficiency can become a major obstacle for the broader use of high frequency laser sources that necessitate high dynamics 3D scanheads for executing cost effectively surface processing operations.

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